Constraining the Nature of Bow Shocks of Runaway Stars through *Fermi*-LAT Observations

Anneli Schulz (DESY)

on behalf of the *Fermi* Large Area Telescope Collaboration

Poster HE 38

Bow Shocks from Runaway Stars

- Runaway stars ($v_* > v_{\text{field stars}}$) with
  - $v_* > v_{\text{SOUND, ISM}}$ (~10 km/s)

- Shock interstellar medium (ISM)
- Create bow shocks
  in direction of motion

http://apod.nasa.gov/apod/image/1102/zetaoph_wise_900c.jpg

Multiwavelength detections:

- Typically infrared and optical wavelength
- One in non-thermal radio
- Maybe X-ray and high-energy gamma

E-BOSS: An Extensive stellar BOw Shock Survey. C. S. Peri et al. 2011

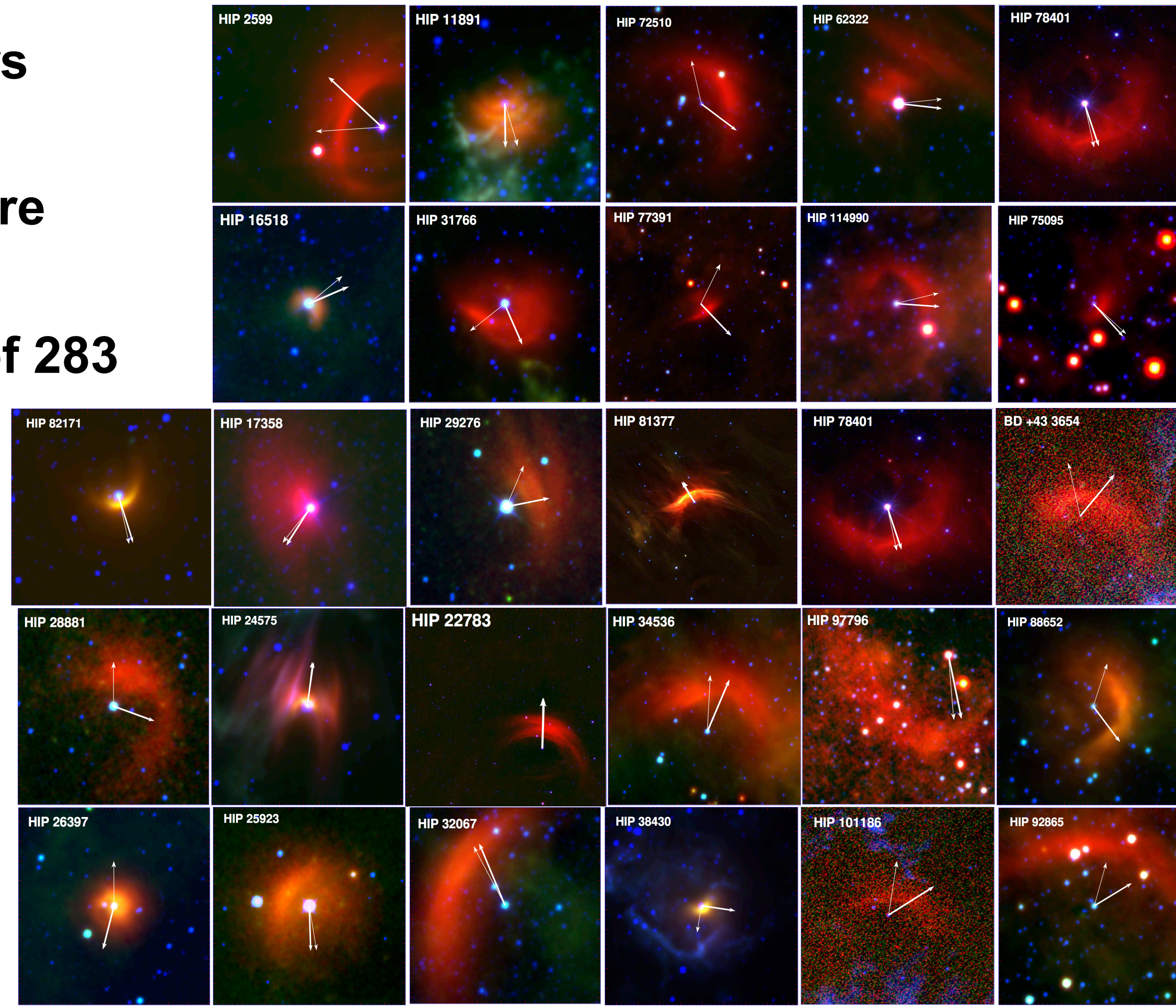
Method:

- OB runaway stars
- $d_* < 3$ kpc
- Arch like structure

28 candidates out of 283

No dependence on

- Position
- Stellar mass
- Age



Bow shock scheme

Star/Shock rest frame

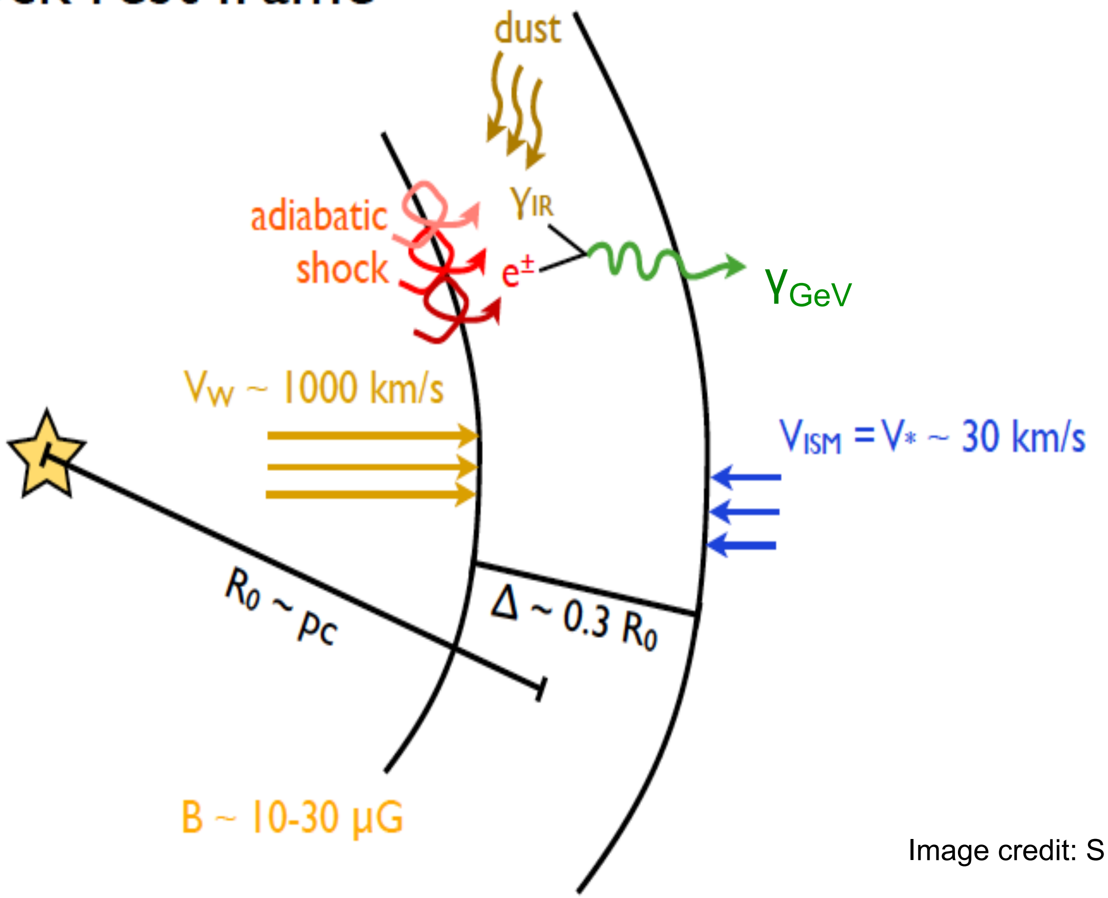
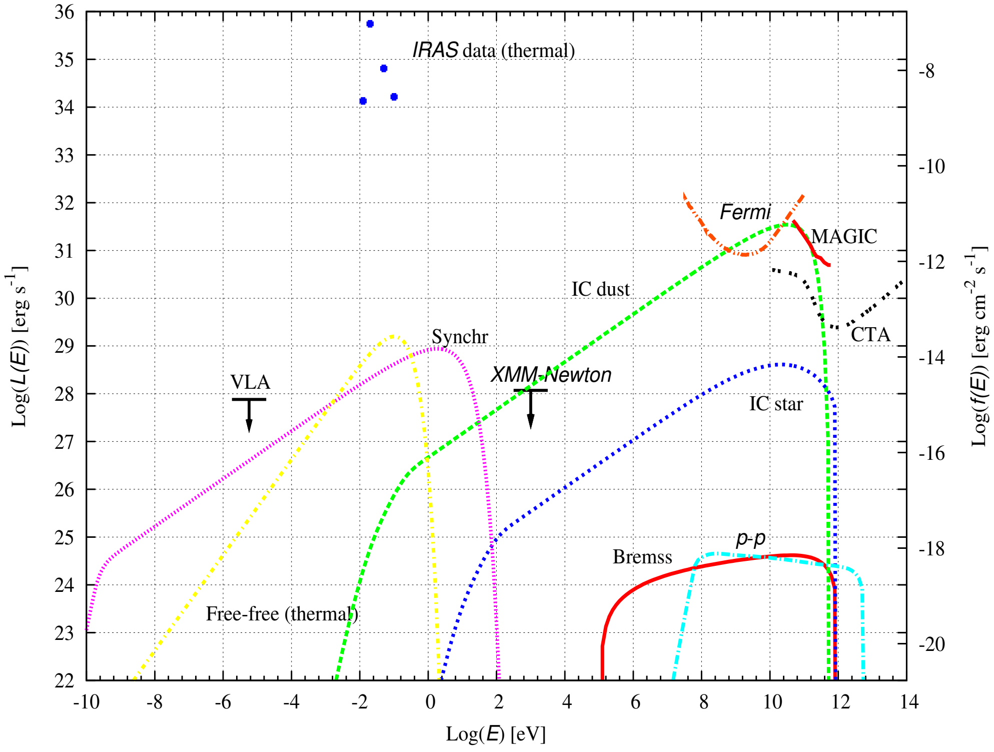


Image credit: S.Klepser

Application of model to ζ Ophiuchi

M. V. del Valle et al. 2012

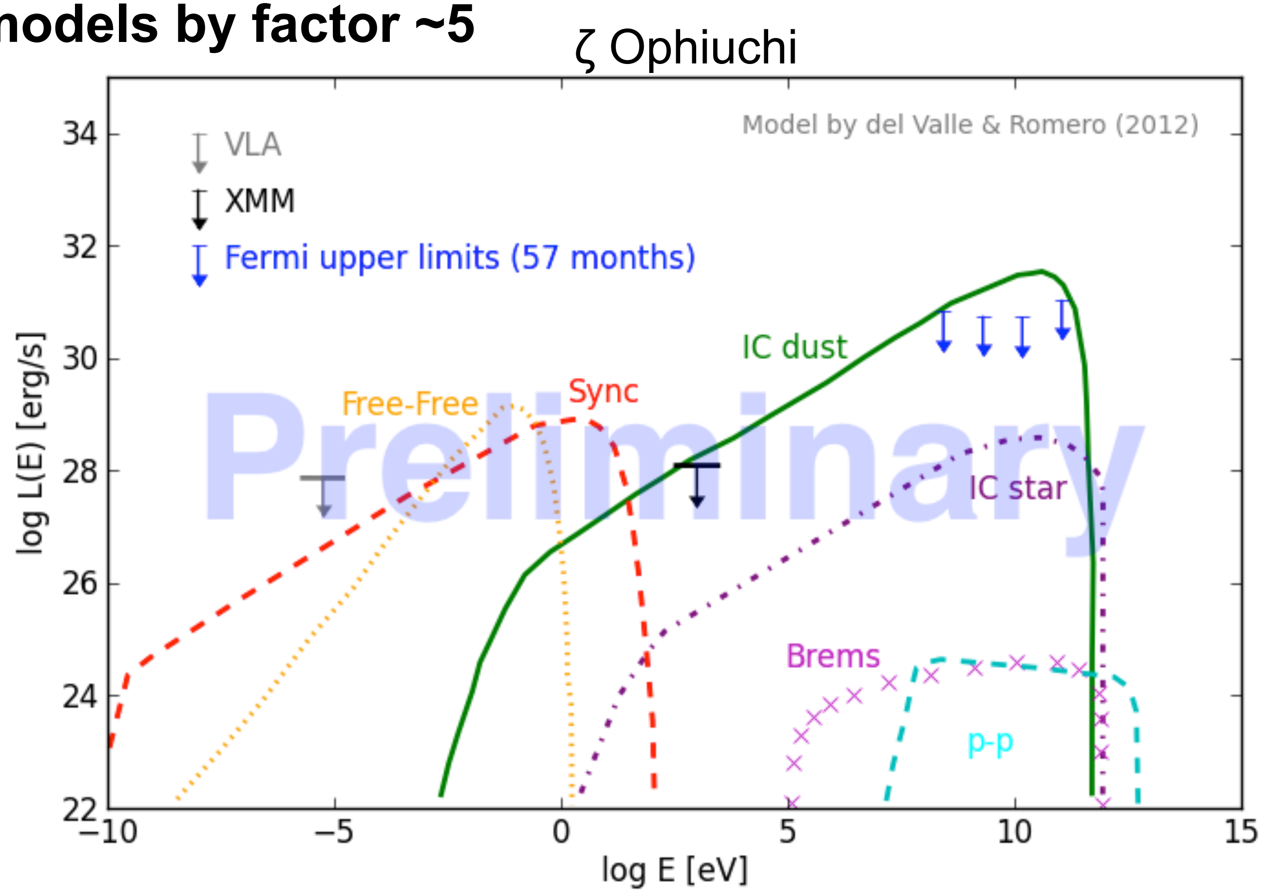
- Well studied bow shock
- d = 222 pc
- Model prediction



Spitzer, Blue: 3.6 and 4.5 μ, green: 8.0 μ, red: 24 μ

Fermi-LAT Upper Limits

- First systematic study searching for high-energy gamma-ray emission (57 months) from bow shocks of runaway stars
- No evidence for gamma-ray emission from the bow shocks
- UL constrain models by factor ~5



Constraining the Nature of Bow Shocks of Runaway Stars through Fermi-LAT Observations

Anneli Schulz (DESY) on behalf of the Fermi Large Area Telescope Collaboration

Abstract

Bow shocks of runaway stars were suggested as possible sources of high-energy gamma-ray emission. In addition to the detection at infrared wavelengths, there have recently been claims for detection in X-rays and radio, indicating a spectrally wide non-thermal component. For the first time we systematically analyzed nearly five years of Fermi-LAT data from the regions of 27 bow shock candidates. These candidates are the ones listed in the E-BOSS catalogue of stellar bow shocks. Since no significant emission was found, we calculated flux upper limits. For one of the candidates (ζ Ophiuchi) a recent prediction of gamma-ray emission can be robustly ruled out by our data. Our flux upper limits on the gamma-ray emission from any of the known stellar bow shocks strongly constrain the possible gamma-ray component that these objects may have.

Bow Shocks of Runaway Stars

Runaway stars can produce bow shocks if they move supersonically through the interstellar medium. There are models (e.g. del Valle et al. 2012) predicting high-energy gamma-ray emission from bow shocks of runaway stars. The main contribution in the high-energy regime are photons from the dust, being upscattered via the Inverse Compton effect.

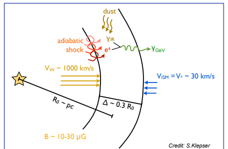


Figure 1: *Scheme of a bow shock from a runaway star in the rest frame of the star.*

We systematically investigate 27 out of the 28 bow shocks found in the E-BOSS catalogue searching for high-energy (E>100 MeV) gamma-ray emission from these objects. HIP 101186 is excluded, since this source is spatially coincident with a gamma-ray pulsar (Pletsch et al. 2012). If either the size of the bow shock exceeds 18′ or the distance between star and shock is larger than 5′ (as listed in Peri et al. 2012) we use templates from publicly available WISE data to search for high-energy emission.

Observation and Analysis

We analyse 57 months of Fermi-LAT data (Pass 7) in a binned likelihood fit using the gtlike package provided within the LAT Science Tools[1] (v9r29p00) in the energy range from 100 MeV to 300 GeV. We use the second Fermi-LAT catalogue (2FGL, Nolan et al. 2012) as input model. If bright emission is apparent in the TS map (as seen in the left map) we introduce a new source at the point of highest emission. The example to the right shows two TS maps for the best candidate. We introduce source A, for which no counterpart has been found so far.

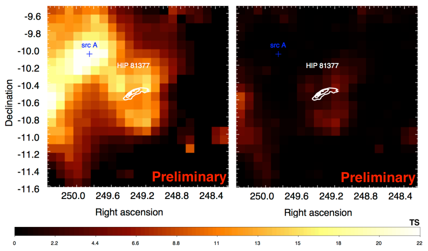


Figure 2: *TS maps of the best candidate ζ Ophiuchi with a bin size of 0.1°. White contours are from the WISE template. Left: including only 2FGL sources in the model. Right: including an additional source A in the model.*

Model Predictions and Upper Limits

Models of the high-energy gamma-ray emission have been published for three of the bow shocks. Fig. 4 and 5 show the LAT upper limits derived in this analysis together with the spectral energy distribution (SED) predicted by published models. For ζ Ophiuchi our limits constrain the model predictions by a factor of ~5. Our upper limits are roughly at the same level as the model predictions in the case of BD +43°3654 and for the third candidate (HIP 24575) the Inverse Compton peak is expected in the X-ray regime, therefore, not in reach for Fermi-LAT.

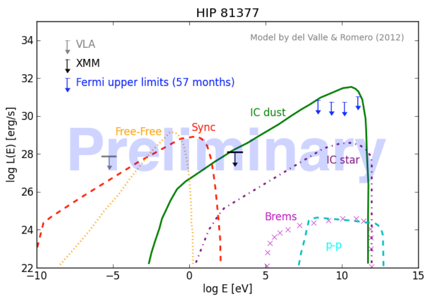


Figure 4: *SED for the best candidate ζ Ophiuchi.*

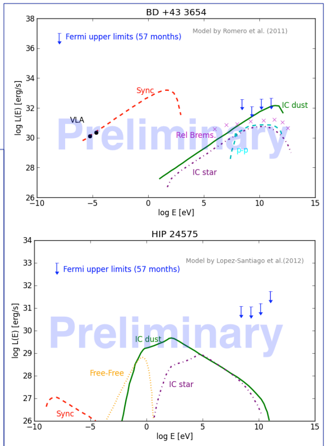


Figure 5: *SED for the two other candidates.*

Fit Verification

To verify the fitted model, we calculate residual count maps. If bright residuals appear at 2FGL background source positions, the fit is repeated with the spectral parameters of these sources left free.

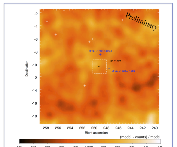


Figure 3: *Residual count map for ζ Ophiuchi.*

Upper Limits

Since all bow shock candidates have TS values smaller than 10, meaning that no significant emission was found, we derive upper limits in four energy bins.

Star	l [°]	b [°]	$\epsilon_\gamma F(\epsilon_\gamma)$ [10^{-6} MeV /cm^2/s^1] 0.1 – 0.74	0.74 – 5.5	5.5 – 41	41 – 300 [GeV]
HIP 24575	172.0813	-02.2592	0.21	0.19	0.28	0.96
HIP 81377*	006.2812	+23.5877	0.72	0.60	0.57	1.16
BD+43°3654	082.4100	+02.3254	1.00	0.33	1.05	1.19

Table 1: 95% confidence-level gamma-ray flux upper limits for bow shocks of runaway stars. Calculated by assuming point sources for two bow shock candidates and a template from WISE data for the other candidate (denoted with a *). *l* and *b* denote the Galactic coordinates of the star. $\epsilon_\gamma F(\epsilon_\gamma)$ corresponds to the differential energy flux within the energy range provided (GeV) assuming a power-law spectrum of gamma-ray emission with photon index α_γ=2.

Conclusions

We present the first systematic study searching for high-energy gamma-ray emission from bow shocks of runaway stars. There is no evidence for gamma-ray emission with E>100 MeV from the bow shocks collected in the E-BOSS catalogue.
The flux upper limits derived from the Fermi LAT data challenge current models of high-energy emission from certain bow shocks.

References

del Valle, M. V. & Romero, G. E. 2012, A&A, 543
López-Santiago, J., Miceli, M., del Valle, M. V., et al. 2012, The APJ Letters, 757, L6
Nolan, P. L., Abdo, A. A., Ackermann, M., et al. 2012, ApJS, 199, 31
Peri, C. S., Benaglia, P., Brookes, D. P., Stevens, I. R., & Isequilla, N. 2012, A&A, 538
Pletsch, H. J., Guillemot, L., Allen, B., et al. 2012, ApJ, 744, 105
Romero, G. E., Benaglia, P., Peri, C. S., Martí, J., & Araudo, A. T. 2011, Bulletin SRSL, 80, 420

[1] Fermi Science Tools, available via http://fermi.gsfc.nasa.gov/ssc

Acknowledgements: The *Fermi* LAT Collaboration acknowledges support from a number of agencies and institutes for both development and the operation of the LAT as well as scientific data analysis. These include NASA and DOE in the United States, CEA/Irfu and IN2P3/CNRS in France, ASI and INFN in Italy, MEXT, KEK, and JAXA in Japan, and the K.A.Wallenberg Foundation, the Swedish Research Council and the National Space Board in Sweden. Additional support from INAF in Italy and CNES in France for science analysis during the operations phase is also gratefully acknowledged.

Literature

- del Valle, M. V. and Romero, G. E. (2012). Non-thermal processes in bow- shocks of runaway stars. Application to ζ Ophiuchi. A&A, 543:A56.
- del Valle, M. V., Romero, G. E., and De Becker, M. (2012). Is the bowshock of the runaway massive star HD 195592 a Fermi source? ArXiv e-prints.
- Lòpez-Santiago, J. et al. (2012). Ae aurigae: First detection of non-thermal x-ray emission from a bow shock produced by a runaway star. The Astro- physical Journal Letters, 757(1):L6.
- Peri, C. S., Benaglia, P., Brookes, D. P., Stevens, I. R., and Isequilla, N. L. (2012). E-BOSS: an Extensive stellar BOw Shock Survey. I. Methods and first catalogue. A&A, 538:A108.
- Romero, G. E., Benaglia, P., Peri, C. S., Mart´ı, J., and Araudo, A. T. (2011). Non-thermal radiation from a runaway massive star. Bulletin de la Societe Royale des Sciences de Liege, 80:420–424.
- Wilkin, F. P. (1996). Exact Analytic Solutions for Stellar Wind Bow Shocks. ApJL, 459:L31.